Luminescent Solar Concentrators for Fibre Optic Daylighting

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CERTIFICATE

I certify that this thesis has not already been submitted for any degree and is not being submitted as part of the candidature of any other degree.

I also certify that the thesis has been written by me and that any help I have received in preparing this thesis, and all sources used, have been acknowledged in this thesis

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Author's Publications

Journal Publications

Earp, A.A., Smith, G.B., Swift, P.D., Franklin, J. (2004).
Maximising the Light Output of a Luminescent Solar Collector.
Solar Energy 76 (6), 655-667.

Earp, A.A., Smith, G.B., Swift, P.D., Franklin, J. (2004).
Optimisation of a three-colour luminescent solar concentrator daylighting system
Solar Energy Materials and Solar Cells 84, 411-426.

Smith, G.B., Earp, A., Franklin, J., Mccredie, G. (2001).
Novel high performance scattering materials for use in energy saving light fittings and skylights based on polymer pigmented with polymer.
Proceedings of SPIE solar and switchable materials, San Diego, CA, United States, pp. 10-18.

Earp, A.A., Smith, G. B. and Franklin, J.
BRDF of a Non-Lambertian diffuse surface at arbitrary angles of incidence
'Lighting Research and Technology (submitted Dec. 2004, publication pending)

Conference Proceedings

Earp, A.A., Smith, G.B., Franklin, J. (2005). Extraction of trapped light from luminescent solar concentrators. *Proceedings of AIP Congress,* ANU, Canberra, pp. 104-107 AIP.

Abstract

Daylight is an abundant source of energy that, if used effectively for lighting in buildings, can improve quality of life and decrease the demand for electric lighting and air-conditioning, reducing energy consumption and costs. Various daylighting systems are available for daylighting the perimeter zones of buildings. However, it is more difficult to transport daylight to remote rooms. The few systems available for remote room daylighting are expensive or disruptive to the building design and rely heavily on direct sunlight.

Luminescent Solar Concentrators (LSC's) contain fluorescent dyes that absorb both direct and diffuse sunlight without tracking the sun, causing fluorescent emission in a specific wavelength range. LSC's can potentially be used for daylighting, but the only previously demonstrated system is rather bulky and architecturally intrusive, and its output is yellow-green and difficult to control. A stack of three coloured LSC's is proposed in this thesis, which produces a good white output of over 1,000 lumens under solar illumination of 100,000 lux. This output is transported to a remote room in narrow flexible polymer light guides.

A theoretical model of the three-colour LSC stack was developed, which uses the absorption and emission spectra of the dyes to predict the LSC's output spectrum and lumens. Studies with this model revealed the importance of highly accurate absorption tails data for good prediction of the stack performance. The model was used to determine the optimum size and dye concentration for each LSC. A simple experimental method was devised for characterising the optical performance of a fixed size LSC.

Half of the emitted light is trapped at the end of the light guides, so a 'light extractor' is required to enable this light to escape. Ray tracing simulations were carried out for various light extractor designs, from which the optimal light extractor size, shape and configuration were determined for maximum optical gain. With a good light extractor design, a gain of 1.7-1.8 should be achievable, but with the current prototypes, the gain is limited to 1.2-1.3, limiting the output to around 1,100 lumens. The violet collector sheet in the LSC stack was also found to be problematic, so an alternative blue light source is proposed. Hence there is room for improvement in future prototypes.

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List of Symbols Used

Symbol	*Description*	Units
$\alpha(\lambda)$	Wavelength-dependent attenuation coefficient of fluorescent dye	m^{-1}
α_m	Attenuation coefficient of polymer matrix (assumed to be wavelength independent)	m^{-1}
$A(\lambda)$	Absorption spectrum of fluorescent dye	
$A(\theta_i)$	Area of pseudo-specular beam as a function of angle of incidence	
A_{det}	Area of detector in photogoniometer	m^2
β	Artificial dye tails attenuation factor (for studying effect of reduced tails attenuation on LSC performance)	
$BRDF(\theta_i, \gamma, \omega)$	Bi-directional Reflectance Distribution Function of white diffuse surface inside light extractor (three-dimensional)	sr^{-1}
$BRDF(\theta_i, \gamma)$ or $BRDF(\theta_i, \gamma)_{Total}$	Bi-directional Reflectance Distribution Function of white diffuse surface inside light extractor (two-dimensional)	sr^{-1}
$BRDF_D(\theta_i, \gamma)$	Diffuse component of two-dimensional BRDF	sr^{-1}
$BRDF_{PS}(\theta_i, \gamma)$	Pseudo-specular component of two-dimensional BRDF	sr^{-1}
χ	Critical angle of reflection from polymer surface	radians
δ	Exponential loss coefficient: taken from slope of output intensity vs. distance; used to calculate half-length $L_{1/2}$	m^{-1}
σ	Deviation angle caused by a single microsphere	radians
$\varepsilon_o(\lambda)$	Emission spectrum of dye molecule	$W.m^{-2}.nm^{-1}$
$\varepsilon(\lambda,L)$	Emission spectrum reaching the end of a LSC of length L	$W.m^{-2}.nm^{-1}$
$\varepsilon_V(\lambda)$	Emission spectrum of violet dye	$W.m^{-2}.nm^{-1}$
$\varepsilon_G(\lambda)$	Emission spectrum of green dye	$W.m^{-2}.nm^{-1}$
$\varepsilon_P(\lambda)$	Emission spectrum of pink dye	$W.m^{-2}.nm^{-1}$
$E_{abs}(\lambda)$	Energy absorbed by dye molecules	$W.m^{-2}.nm^{-1}$
E_e	Total power emitted by dye molecules	$W.nm^{-1}$
$E_{VT}(\lambda)$, $E_{GT}(\lambda)$, $E_{PT}(\lambda)$	Transmitted solar energy incident on the violet, green and pink sheets respectively	$W.m^{-2}.nm^{-1}$

Symbol	*Description*	Units
$E_{VR}(\lambda)$, $E_{GR}(\lambda)$, $E_{PR}(\lambda)$	Solar energy reflected from the white base of the stack, incident on the violet, green and pink sheets respectively	$W.m^{-2}.nm^{-1}$
$E_{GE}(\lambda)$	Emitted energy from the violet sheet, incident on the green sheet	$W.m^{-2}.nm^{-1}$
$E_{PE}(\lambda)$	Emitted energy from the green sheet, incident on the pink sheet	$W.m^{-2}.nm^{-1}$
F_o	Ratio of trapped light to endlight at point of dye emission	
F_t	Fraction of emitted rays that are trapped (outside all critical loss cones)	
F_e	Fraction of emitted rays within the critical angle loss cones with respect to the collection edge or mirror edge of the collector	
$F_{at}(\lambda)$	Ratio of trapped light to endlight at end of fixed length collector (varies with wavelength)	
$\overline{F}_t$	Mean fraction of trapped light at the end of a fixed length collector, weighted over the dye emission region	
$\overline{F}_e$	Mean fraction of endlight at the end of a fixed length collector, weighted over the dye emission region	
$\overline{F}_{at}$	Mean ratio of trapped light to endlight at the end of a fixed length collector, weighted over the dye emission region	
Φ_L	Luminous flux at end of uniformly illuminated LSC	lumens
Φ_l	Luminous flux at end surface of LSC when illuminated by a line source at a distance l from end	lumens
Φ_{obs}	Observed luminous flux from end surface of LSC;	lumens
φ	Lux to lumens conversion factor for integrating sphere	
γ	Deviation angle from surface normal in horizontal plane	radians
γ_s	Deviation of reflected ray from specular direction inside light extractor	radians
$\overline{G}$	Optical gain induced by installation of a light extractor to a collection edge or light guide end, weighted over the emission region of the dye	

Symbol	*Description*	Units
η_e	Energy-to-energy conversion efficiency of fluorescent dye	
η_{ll}	Light-to-light efficiency of a LSC sheet	
η_q	Quantum efficiency of fluorescent dye	
η_o	*Collection edge endlight efficiency*; fraction of light within the critical angle cone with respect to the collection edge that is transmitted on its first pass	
η_{trap}	*Light extractor trapped light efficiency*; fraction of trapped light striking front surface of light extractor that is transmitted, on the first or a subsequent pass	
η_{end}	*Light extractor endlight efficiency*; fraction of endlight striking front surface of light extractor that is transmitted, on the first or a subsequent pass	
$\overline{\eta}$	*Overall light extractor efficiency;* fraction of light entering a light extractor that is transmitted through the front surface	
H	Height of light extractor	m
I_{in}	Incident beam signal in photogoniometer	mV
$I_{ref}(\theta_i, \gamma, \omega)$	Reflected signal from white diffuse surface	mV
I_{end}	Measured signal from output of polished end of LSC, when illuminated by fluorescent lamp a fixed distance from the end	mV
I_{le}	Measured signal from light extractor on end of LSC, when illuminated by fluorescent lamp a fixed distance from the end	mV
I_{sphere}	Illuminance on Hagner photopic detector in integrating sphere when used to measure luminous output of end surface of LSC	lux
I_{sol}	Solar illuminance incident on LSC	lux
K	Mean reflectivity correction factor of integrating sphere interior surface, weighted over dye emission region and photopic response $V(\lambda)$	
$L(\theta_i, \gamma_s)$	Lorentzian function describing direction of pseudo-specular reflected rays, as a function of angle of incidence and deviation from specular direction	
L	Length of fluorescent sheet	m
$L_{d½}$	Half-length component from fluorescent dye	m

Symbol	*Description*	**Units**
$L_{m1/2}$	Half-length component from clear matrix	m
l	Horizontal distance from point of fluorescent emission to end surface of LSC	m
λ	Wavelength of radiation	nm
λ_{exc}	Peak wavelength of excitation beam	nm
Ψ	Wavelength of excitation radiation	nm
λ_{min}, λ_{max}	Wavelength limits for emission measurements	nm
LSC	Luminescent Solar Concentrator	
<m>	Average distance between microspheres	m
$\mu(\theta_i)$	Effective radius of cylinder containing pseudo-specular reflected ray distribution in cylindrical co-ordinates	m
n	Refractive index	
$P_D(\theta_i)$	Probability of diffuse reflection from a white diffuse surface as a function of angle of incidence, θ_i	
$P_{PS}(\theta_i)$	Probability of pseudo-specular reflection from a white diffuse surface as a function of angle of incidence, θ_i	
$P(x)$	Probability of a ray striking a microsphere after travelling a distance x in a TRIMM-doped light extractor or diffuser sheet	
θ	Altitude angle with respect to vertical axis of LSC	radians
ϕ	Azimuthal angle with respect to collection edge of LSC	radians
θ_i	Angle of incidence of ray with respect to surface normal	radians
$\theta_o(\theta_i)$	Pseudo-specular Lorentzian peak-angle parameter as a function of angle of incidence	
$\rho_{DHD}(\theta_i)$	Diffuse component of direct-hemispherical reflectance from white diffuse surface as a function of angle of incidence	
$\rho_{DHPS}(\theta_i)$	Pseudo-specular component of direct-hemispherical reflectance of white diffuse surface as a function of angle of incidence	
r	Radius of rotation of photogoniometer detector	m
R_c	Reflectivity of cover sheet	
R_m	Reflectivity of mirror on back end of collector sheets	

Symbol	*Description*	**Units**
$R(\theta_i)$	Radius of pseudo-specular beam as function of angle of incidence	
$\overline{R}$	Weighted mean Fresnel surface reflectance over critical angle cone at collection edge	
$R_{sph}(\lambda)$	Spectral response of integrating sphere interior surface	
$R_{norm}(\lambda)$	Normalised spectral response of integrating sphere, weighted over dye emission region and photopic response $V(\lambda)$	
$S(\lambda)$, $S(\Psi)$	Solar spectrum incident on fluorescent sheet	$W.m^{-2}.nm^{-1}$
t	Thickness of fluorescent sheet	m
$T_{fl}(\lambda)$	Fluorescent component of transmission measurements	
$T_D(\lambda)$	Transmission spectrum of fluorescent dye (excluding Fresnel losses) – generic term	
$T_{LSC}(\lambda)$	Transmission of collector sheet (including Fresnel losses) – generic term	
$T_M(\lambda)$	Transmission of clear polymer matrix (excluding Fresnel losses)	
$T_{Clear}(\lambda)$	Transmission of clear polymer matrix (including Fresnel losses)	
$T_C(\lambda)$	Transmission of cover sheet (including Fresnel losses)	
$T_G(\lambda)$	Transmission of green dye in LSC (excluding Fresnel losses)	
$T_P(\lambda)$	Transmission of pink dye in LSC (excluding Fresnel losses)	
$T_V(\lambda)$	Transmission of violet dye in LSC (excluding Fresnel losses)	
$V(\lambda)$	Photopic response of the human eye	
w	Width of fluorescent sheet	m
$w(\theta_i)$	Lorentzian width as a function of angle of incidence for pseudo-specular reflected rays	radians
ω	Rotational angle around specular direction	radians
W	Width of light extractor	m
Ω_{lc}	Solid angle enclosed by a single critical loss cone	steradians
Ω_e	Solid angle enclosed by endlight (escaping light) at collection edge	steradians
$\Delta\Omega_{det}$	Solid angle of detector in photogoniometer	steradians